Verification of Durability of Novel Applications

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Summary

Durability of structural concrete can be assessed according to standards, when the degradation models of materials and their combinations as well as experiences from the use are available in a reliable way. In the case of innovative structural materials and applications, the needs to verify durability may lead to extensive studies on the application of current methods. A state-of-the-art of durability verification of functional concrete materials and steel-concrete composite structures shows that existing knowledge is in common adaptable but needs interpretation and systematic identification of risks. However, there are several sources of uncertainty in the methods themselves like e.g. the influence of loading. Further, interaction between different materials inside a structure is in some examples an additional source of chemical reactions and degradation, but the service life design methods typically rely on environmental classes.

KEYWORDS
Concrete product, durability, service life, testing, evaluation

1. Introduction

For all kinds of works, durability is a major requirement that is included in all six essential requirements of the Construction Products Directive (89/106/EEC) of the European Community. In the Guidance Paper F related to the Directive, durability has been defined as “the property of lasting for a given or long time without breaking or getting weaker.” Further, durability aspects are linked to the “working life” that means the “period of time during which the performance of the works will be maintained at a level compatible with the fulfilment of the essential requirements. The widely used ISO Standard 15686 defines durability as the “capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service”, and it further notes that “Durability is not an inherent property of a material or component, although the term is sometimes erroneously used as such.” In other words, durability refers to the ability of a product to resist deterioration from the environment or from the service in which it is placed.

Durability of a structure depends on the physical, chemical and mechanical properties of materials as well as composition and lay-out of the structure with respect to the actions that may result in degradation. Durability of known types of products and solutions can usually be assessed based on existing knowledge and existing standards and methods. There are also various analytical degradation or durability models available. In these kinds of situations, the deem-to-satisfy approach is justified to be applied in service-life design.

Durability of new construction solutions made of concrete has often been poor compared with expectations. The consistence of materials or their combinations or production methods are examples of causes that have resulted to premature deterioration of solutions in use. When the problem of durability appears, it often results to expensive repair work. In order to make more reliable service-life design and life-cycle analysis, the durability models need to be based on the actual deterioration mechanisms. On the other hand, the needs to verify the durability may cause delays on the launch of novel applications or unwillingness to participate in development efforts as the scientific work seems to be complicated and confusing.

In this paper, aspects of verification of durability of novel concrete applications are studied based on literature survey and findings of experimental projects. The findings are considered in relation to the product approval procedures in which a manufacturer or a designer should be able to show evidence of the product information.

2. Durability and service life design

The problems associated with concrete durability are according to Neville [1] due to poor understanding of deterioration processes, inadequate acceptance criteria and changes in cement properties and construction practices.

In Finland, many of concrete durability problems have occurred in facades. For example, Piironen, Sistonen and Huovinen [2] give background information about their case studies on facades, like a bad condition of washed concrete surfaces within 18-25 years. Sistonen et al [3] conclude that durability of concrete structures has been lower than predicted in outdoor conditions.

Knowledge on various factors and parameters affecting durability is the basis for service life design. For a designer, a manufacturer should be capable to give product information.

2.1 Issues of testing

Knowledge on deterioration phenomena and the factors affecting durability of structural concrete is in principle empirical. Durability is usually assessed based on testing standards or commonly accepted methods, like long-term and short-term weathering tests, mechanical tests (like e.g. vibration, impact) and corrosion tests. The list of so called durability tests often contains the following studies: strength and Young modulus, carbonation depth, pore size distribution, chloride permeability and freezing-thawing. The durability models and calculation formula also need experimental data.

Various standardised testing methods on hardened concrete are frequently used in continuous quality control or as a part of research and development. However, the suitability of current testing methods has often been criticised due to the poor correlation with field tests or indicating only a part of relevant factors. There are also different applications of the methods that results to interpretation problems. Some of the tests take a long period of time.

Field tests are in general regarded as inaccurate and inconsistent [4]. Often is little known about the background of the observations [5].

2.2 Issues of modelling

Mathematical models for deterioration of concrete structures are developed since early stages of research. The reliability of a model depends to great extent on the reliability of empirical data. Lindvall [5] argues that in reality only those models that are related with corrosion of reinforcement are useful. According to Watanabe [6], mathematical prediction of durability is impossible due to a big amount of parameters, but the effects of heat and moisture coupled transfer can be predicted. In his paper, a reference is also made to the application of damage mechanics as a new approach to concrete durability problems.

Traditionally, the most studied durability factors are those that initiate and propagate corrosion of the reinforcement as the succeeding damages have significant economic impacts in infrastructure. The following causes are recognized to have lead to a quick corrosion process [7]: defrosting salts in bridges and parking lots, sewage waters, alternating periods of moisture and drying in see structures, additives of concrete, uncompleted burning of light-weight aggregates of concrete, steel parts on surfaces and connectors.

For the reinforced concrete, ingress of chlorides is the most dangerous cause for corrosion. In transportation of chloride ions, the governing factors of diffusion are water to cement (w/c) or water to binder (w/b) ratios, temperature, mutual effect of cation coexisting with the chloride ion, type of exposure conditions, curing temperature, cement type, supplementary cementing materials [8]. Rate of diffusion depends also on factors that are less studied like curing conditions [9].

Recently, concern has been presented on the lack of loading effects on the durability models. Yoon et al [10] emphasize that for a rational service life prediction, influence of the service load on the performance should be considered in combination with environmental conditions and material proportions.

In cold climates, the physical frost damages are quite common. They result from alternative freezing and thawing, and in humid outdoor conditions they appear as scaling and cracking of concrete [11]. Modelling of frost resistance is based upon an experimental coefficient, which is test-specific. The patterns of damages are dependent on the saltiness of the moisture, too.

2.3 Issues of service life design

The scale of verification of durability extends from simplistic design conditions to statistical models. In design codes and standards, it is common to specify w/c ratio and minimum thickness of the concrete cover that are dependent on environmental classification. Stringent rules can also be given to other design variables like e.g. percentage of chlorides in cement or amount of cement. The targeted years of service life are expected to be achievable following these rules. The opposite approach is performance based design that would use mathematical and theoretical models for durability, for which methods are under development.

In design, the definitions related to durability are often selected based on the ISO standard 15686 [12] and the most important of them are the estimated service life and reference service life of component: Estimated service life depends upon the reference service life together with seven multiplying factors. The stochastic nature of the service life may be taken into account in the reference value. The quality of manufacture, design and construction, environmental conditions as well as use and maintenance are taken into account with the multiplying factors but they may also be included in a service life model.

In decision making, the estimated service life is evaluated against the target or limit that has been defined either from structural, economic or aesthetic points of views. Corrosion may have aesthetic and structural consequences and in worst cases the loss of interaction between concrete and rebars or reduction of the steel area may lead to failure. In estimating of the service life of concrete structures like facades, spalling of concrete cover is often regarded as the limit state. In tensioned structures, the service life is the period during which the passive surface layer of the steel is destroyed for any reason.

The reliability of service life design is greatly dependent on the methods to define the reference service life or the durability models and the use of the multiplying factors.

3. Studies on novel applications

3.1 Discoveries in the literature

Examples of premature degradation of a concrete structure are numerous in the literature. A lot of cases are related to severe environments or chemical attacks as mentioned above. In recent years, when use of admixtures and additives, various cementing materials and recycled concrete has increased, more examples are related to less investigated factors.

In the International Symposium on High Performance Concrete, Konig et al [13] reported about observations on unusual reduction of compressive strength which took place especially if concretes were exposed to high temperatures during the hydration, such as inside a structure component. Also, it was observed that for some HPC the frost de-icing salt resistance is considerably lower than expected. The effect of curing conditions on the early-age properties and long-term durability of HPC is not yet fully understood. Newer investigations confirm a stronger tendency to the forming of microcracks in concrete with extreme low w/c ratios or with increasing age. Both the reasons for the stronger formation of microcracks and the resulting concrete properties, especially the durability, are not completely clarified yet.

The durability problems of glass fibre reinforced cement / concrete (GRC) have been observed in wet environments [14]. The underlying mechanisms are complex, but the fundamentals are that as the cement matrix continues to 'cure' over a period of years, crystals of calcium hydroxide (CH, slaked lime) form on and around the bundles of glass fibres. These crystals interact with the fibres in such a way as to slowly weaken them, degrading the composite. The high alkalinity of ordinary cement matrices significantly aggravates this effect.

The effects of recycled concrete or recycled materials like plastic or paper on durability of concrete are studied more and more [15, 16]. The high water consumption needed with recycled concrete aggregate increases the shrinkage and reduces the strength which is a major obstacle to structural use. The same effect is related to the use of manufactured aggregates [17].

3.2 Studies on composite structures

Composite steel-concrete structures involve new aspects on the durability issues. In addition to the degradation mechanisms of a reinforced concrete structures, the corrosion mechanisms of the steel part need to be taken into account when the steel surface is exposed to the environmental effects.

A special type of composite construction is a composite slab comprising of concrete and thin galvanized steel sheet. Based on literature survey [18], chemical reactions between the protecting zinc layer and fresh concrete take place during concreting. They consumes zinc layer that is usually 20 μm on both sides of the steel sheet but they also results to a new passive layer of zincates that protects the steel when the pH of concrete is less than 12.5. Within the first hours of hardening, the pH of concrete is higher to 13 and during those hours protective zincates may dissolve in the concrete. The reactions also release hydrogen that forms bubbles on the interface of steel part and concrete. This phenomenon depends on the properties of cement and mixture of concrete. It is also known that zinc has a limited resistance against chlorides, sulphides and alkalines. The layer with porosity, dissolving of zincates and consumption of zinc may influence on the durability of the structure in various ways depending on the conditions of the use.

The published results of other experimental studies clearly show that the passive layer on zinc is highly unstable and does not withstand chloride attack. Harass et al [19], conclude that zinc delays the onset of corrosion of steel by sacrificantly dissolving but it corrodes at a faster rate in the presence of chloride ions.

3.3 Discussion

Based on literature surveys and experimental studies, the complexity of durability problems of concrete seems to be overwhelming from the points of view of practical engineering and development of novel materials or solutions. The accelerated testing methods are developed in relation to the materials under investigation, and for new types of materials new factors may become more relevant. The interpretation of current methods has also been questioned, and a requirement is presented that they should better fit with the critical factors in service.

However, the framework for the innovative applications can be rationally developed based on cumulated long term experiences and theoretical understanding of durability of concrete structures. The examples given above have led to extensive investigations, including the testing methods and field observations on concrete materials but also on the effects of mixing, casting and curing of concrete. In general, capacity of computers and advanced modelling have prospects to shorten the time to get reliable data concerning durability. New approaches to analyze the degradation mechanism are under development.

4. Durability verification

When developing a new material or manufacturing technologies for a construction product or a new application like composite construction, the risks associated with the premature deterioration should be recognized. For engineering, the concluding lists of various parameters essential for the most risky phenomena can be used as a starting point to evaluate effects of new solutions on the durability. Existing knowledge is in common adaptable but needs interpretation and systematic identification of risks. Further, the sources of uncertainty in the methods themselves like e.g. the influence of loading need to be identified and their weight should be evaluated. In Table 1, the durability factors are presented.

Table 1. Degradation factors and their effect in the performance [20]

Degradation factors	*Process*	*Effect in the performance*
Mechanical		
Static load	Deformation	Deflection, cracking, rupture
Cyclic load	Fatigue, deformation	Deflection, cracking, rupture
Impact load	Fatigue	Vibration, deflection, cracking, rupture
Biological		
Micro-organisms	Acid production	Leaching
Bacteria	Acid production	Leaching
Chemical		
Pure water	Leaching	Concrete disaggregation
Acids	Leaching	Concrete disaggregation
Acids and acid gases	Neutralization	Steel depassivation
Carbon dioxide	Carbonation	Steel depassivation
Chlorides	Penetration, destruction of passive layer	Steel depassivation
Steel depassivation + H_2O + O_2	Steel corrosion	Steel expansion, reduction of adhesion
Stress + Chlorides	Steel corrosion	Post-tension cables rupture
Sulphates	Crystal pressure	Concrete disaggregation
Aggregates (silica) + alkalis	Silica reaction	Expansion, disaggregation
Aggregate (carbonate) + alkalis	Carbonate reaction	Expansion, disaggregation
Physical		
Temperature variation	Expansion / Contraction	Confined deformation
Humidity variation	Retraction and expansion	Confined deformation
Low temperature + water	Ice formation	Concrete disaggregation
Defrost salt + frost	Heat transfer	Concrete detachment
Ice (sea)	Abrasion	Detachment, cracking
Traffic	Abrasion	Detrition and rupture
Running water	Erosion	Superficial damages
Turbulent water	Cavitation	Cavities
Electromagnetic		
Electricity	Steel corrosion	Steel expansion, reduction of adhesion
Magnetic	Steel corrosion	Steel expansion, reduction of adhesion

5. Conclusions

Concrete is a traditional and extensively used industrial construction material that has been largely developed based on empirical and theoretical research. Cements, aggregates, admixtures, additives, supplementary materials as well as mixing and curing are constantly under development. This brings new requirements on the accelerated test methods and reliable models of durability.

For a developer of a novel material or structural application, knowledge on durability assessment is necessary but difficult to interpret and use. In order to speed up the intake of scientific result into practice, selecting of appropriate and reliable methods should be made easier in the way of scientific models with user-friendly interfaces. In this way, product approval procedures may become faster and durability problems avoided, too.

References

[1] Neville, A. Why we have concrete durability problems. ACI SP-100, *Katherine and Bryant Mather Int. Conf. on Concrete Durability*, American Concrete Institute, Detroit, MI. pp. 21-48.

[2] Piironen, J., Sistonen, E. and Huovinen S., *Life Cycle of Repair Works of Rock Based Facades*, Helsinki University of Technology, Laboratory of Structural Engineering and Building Physics Publication TKK-TRT-125, Espoo, 2003, 97 p + App. 39 p.

[3] Sistonen, E., Tukiainen, P., Laitala, M. and Huovinen, S., *Restricting Corrosion Risk in Reinforced concrete Structures under Outdoor Conditions*, Helsinki University of Technology, Laboratory of Structural Engineering and Building Physics Publication 111, 141 p.

[4] Li, C. Q. Corrosion Initiation of Reinforcing Steel in Concrete under Natural Salt Spray and Service Loading – Results and Analysis, *ACI Materials Journal* 97(2000)6, p. 690 – 702.

[5] Lindvall, A. Duracrete – probabilistic performance based durability design of concrete structures. Proc. on *2nd Int. PhD Symposium in Civil Engineering*, Budapest 1998.

[6] Watanabe, K. General strategies for predicting physical durability of buildings and building components. In Proc. of *1st Asia/Pacific Conf. on Harmonisation of Durability Standards and Performance Tests for Components in Buildings and Infrastructure*, 8-10 of Sept., 1999,. Bangkok, Thailand.

[7] Cornet, I. Galvanized steel in concrete: Literature Review and Assessment of Performance in Galvanized Reinforcement for Concrete II. New York 1981lnInt. Lead Zinc Research Organisation, Inc. p. 3-55.

[8] Suryavanshi, A.K., Swamy, R.N. & Cardew, G.E. Estimation of diffusion coefficients for chloride ion penetration into structural concrete, *ACI Materials Journal* 99(2002)5, p

[9] Haaton, R.D., Geiker, M.R. & Bentz, E.C. Effects of curing on chloride ingress and implications on service life, *ACI Materials Journal* 99(2002)2, p. 690 – 702

[10] Yoon, S., Wang, K., Weiss, W.J. & Shah, S.P. Interaction between loading, corrosion and serviceability of reinforced concrete, *ACI Materials Journal* 97(2000)6, p. 637 – 644.

[11] Vesikari, E. Service life design of concrete structures againt frost attack and corrosion of reinforcement, RIL K77 & by 134, *Special course on design of concrete structures IV*. Suomen Betoniyhdistys r.y. ja Suomen Rakennusinsinöörien Liitto ry. 1987.

[12] ISO 15686-1. Buildings and Constructed Assets – Service Life Planning, Part 1: General Principles, ISO/TC59/SC14. 2000, 41 p.

[13] Konig, G.., Krumbach, R., Friedemann, K., Seyfarth, K. & Heinrich U. Proc. 2000 International HPC Symposium, Orlando, Fl.

[14] http://www.eng.warwick.ac.uk/staff/pp/research.htm

[15] Shayan, A. & Xu, A. Performance and properties of structural concrete made with recycled concrete aggregate. *ACI Materials Journal* 100(2003)3, p. 203-207.

[16] Soroustian, P., Plasencia, Y, & Ravanbakhs, H. Assessment of reinforcing effects of recycled plastic and paper in concrete, *ACI Materials Journal* 100(2003)5, p. 371-380.

[17] Lindvall, A. *Environmental Actions and Response, Reinforced Concrete Structures Exposed in Road and Marine Environments*. Dept. of Building Materials. Chalmers University of Technology, Göteborg 2001.

[18] Koukkari, H. Durability of steel concrete composite structures. Preliminary study. Internal report RTE38-IR-1/1996. Technical Research Centre of Finland. Espoo 1996. 22 p.

[19] Harass, B.S., Popov, B.N., Petrou, M.F. & White, R.E. Studies on Galvanized Carbon Steel in Ca(OH)2 Solutions, *ACI Materials Journal* 97(2000)4, p.

[20] Machado, M.P. & Correia, M. C. *Evaluation of Steel Corrosion in Reinforced Concrete Structures*. University of Minho, Dept. of Civil Engineering. Guimarães 2004. 138 p.